REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
February 1993

3. REPORT TYPE AND DATES COVERED
professional paper

4. TITLE AND SUBTITLE
ASYMMETRIC MICROSTRIP LINES ON ANISOTROPIC SUBSTRATES WITH MATERIAL AXES INCLINED IN THE TRANSVERSE PLANE

5. FUNDING NUMBERS
In-house funding

6. AUTHOR(S)
T. Q. Ho and B. Beker

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Command, Control and Ocean Surveillance Center (NCCOSC)
RDT&E Division
San Diego, CA 92152–5001

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Naval Command, Control and Ocean Surveillance Center (NCCOSC)
RDT&E Division
San Diego, CA 92152–5001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Authorized for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

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Published in IEE Proceedings–H, Vol. 139, No. 5, October 1992.

14. SUBJECT TERMS
frequency-dependent characteristics
biaxial substrates
asymmetric microstrip

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAME AS REPORT

21a. NAME OF RESPONSIBLE INDIVIDUAL	21b. TELEPHONE (include Area Code)	21c. OFFICE SYMBOL
T. Q. Ho	(619) 553-3783	Code 824

Asymmetric microstrip lines on anisotropic substrates with material axes inclined in the transverse plane

T.Q. Ho
B. Beker

Indexing term: Microstrip and stripline

Abstract: The frequency-dependent characteristics of shielded asymmetric microstrip lines on uniaxial and biaxial substrates are presented in this memorandum. The permittivity tensor of the supporting medium is assumed to have off-diagonal elements due to the misalignment between the waveguide co-ordinate system and that of the material. New data for the dispersive properties of the asymmetric structure are provided for frequencies up to 40 GHz.

1 Introduction

Anisotropy is observed in a variety of practical substrates that are intended for use in microwave and millimeter-wave integrated circuits (MICs). The anisotropy in some materials, e.g. boron nitride and sapphire occurs naturally, whereas in others, such as in the Epsilam-10 substrate, it is acquired during the fabrication process. As a result, the propagation properties of microstrip lines printed on these substrates are quite different from those printed on commonly used isotropic materials [1–2].

Until now, in the study of microstripline-guiding structures, there are only a few fullwave approaches that take into account the off-diagonal elements of the permittivity tensor. In the work of Tsalamengas [3], open microstrip lines printed on anisotropic substrates were examined; however, no data on their dispersive characteristics due to the off-diagonal elements were provided. In a more recent paper by Geshiro *et al.* [4], another fullwave approach for analysing the same structure is presented, along with some data on the effects of misalignment, which is in the longitudinal plane along the direction of propagation.

For shielded MICs, dispersion characteristics were presented for edge-coupled lines printed on substrates whose principal axes of the permittivity are inclined in the transverse plane [5]. More recently, for substrate materials that are simultaneously characterised by permittivity and permeability tensors, fin-line structures were also analysed using the spectral-domain techniques [6].

In this memorandum, the characteristics of shielded asymmetric microstrip lines printed on either uniaxial or biaxial substrates are examined. This study, unlike some others conducted earlier, treats the geometry of the guiding structure as being asymmetric about the centre of the housing. Such structures are often encountered in practice as many times the maximum use of substrate space is the goal of the design. The propagation properties of the asymmetric microstrip lines are examined in detail, especially when they are printed close to the side walls of the enclosure. In addition, a study to see how the misalignment between the material co-ordinate system and that of the waveguide effects the propagation properties of these lines is also conducted. The formulation of this problem is based on the spectral domain method.

2 Theory

The cross-section of the shielded asymmetric microstrip line under investigation is shown in Fig. 1. The metal

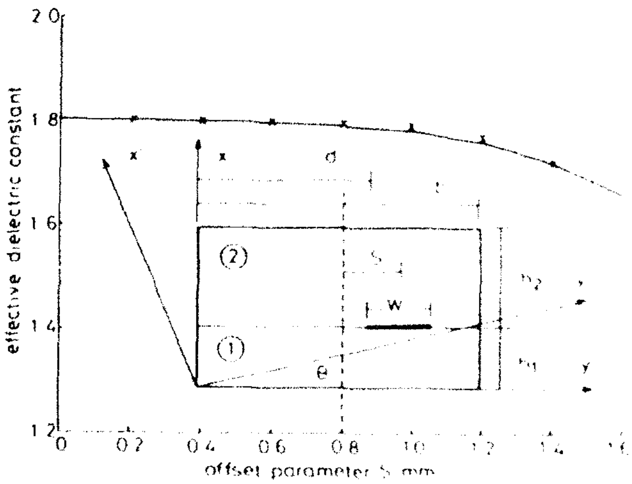

Fig. 1 *Geometry and dispersion characteristics of shielded asymmetric microstrip line on isotropic substrate*

—— This method
× × Schmidt [8]

strip of width W that is printed on top of the anisotropic layer of thickness h_1, is situated inside a housing of dimensions b and $(h_1 + h_2)$. The strip is located a distance d away from the left-hand side wall, and the spacing between the centre of the metal strip and the

Paper 8896H (E12), received 30th March 1992

T.Q. Ho is with the NCCOSC, RDT&E Division, San Diego, CA 92152, USA

B. Beker is with the Department of Electrical and Computer Engineering, University of South Carolina, Columbia, SC 29208, USA

centre of the housing is S [illegible]. The substrate, which extends along the y co-ordinate from 0 to b, is characterised by its permittivity tensor

$$[\varepsilon] = \varepsilon_0 \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} & 0 \\ \varepsilon_{yx} & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{bmatrix} \tag{1a}$$

with

$$\begin{aligned} \varepsilon_{xx} &= \varepsilon_2 \sin^2\theta + \varepsilon_1 \cos^2\theta \\ \varepsilon_{xy} &= \varepsilon_{yx} = (\varepsilon_2 - \varepsilon_1)\sin\theta\cos\theta \\ \varepsilon_{yy} &= \varepsilon_2 \cos^2\theta + \varepsilon_1 \sin^2\theta \\ \varepsilon_{zz} &= \varepsilon_3 \end{aligned} \tag{1b}$$

where ε_1, ε_2 and ε_3 are the principal values of the tensor, ε_0 is the free-space permittivity, and θ is the rotation angle between the material co-ordinates and those of the waveguide.

To formulate the boundary-value problem in the spectral domain, the following definition for the Fourier transform is employed.

$$\tilde{\Phi}(x, \alpha) = \int_{-b/2}^{+b/2} \Phi(x, y) e^{j\alpha y}\, dy$$

with

$$\alpha = \frac{2n\pi}{b} \quad n = \cdots -3, -2, -1, 0, 1, 2, 3, \ldots \tag{2}$$

where $\tilde{\Phi}$ denotes any component of the E- or H-field, which due to the asymmetry of the structure must include both sine and cosine (or exponential) terms. The solutions for the tangential electric fields in the anisotropic region can be obtained by solving the following fourth-order differential equations

$$\frac{d^4\tilde{E}_{y,z}}{dx^4} + c_1, d_1 \frac{d^3\tilde{E}_{y,z}}{dx^3} + c_2, d_2 \frac{d^2\tilde{E}_{y,z}}{dx^2} + c_3, d_3 \frac{d\tilde{E}_{y,z}}{dx} + c_4, d_4 \tilde{E}_{y,z} = 0 \tag{3a, b}$$

The coefficients c_1 and d_1 through to c_4 and d_4, which appear above, can be written in terms of the medium parameters, the transform variable α and the propagation constant β; all of which are defined in Reference 6. In the isotropic region, the corresponding electric-field components can be derived in terms of the potential functions for either the TM or TE fields, as described in Reference [7].

By applying the appropriate boundary conditions for the electric and magnetic fields at the air-anisotropic-layer interface, i.e. at $x = h_1$ the following set of matrix equations can be obtained

$$\begin{bmatrix} \tilde{Z}_{zz}(\alpha, \beta) & \tilde{Z}_{zy}(\alpha, \beta) \\ \tilde{Z}_{yz}(\alpha, \beta) & \tilde{Z}_{yy}(\alpha, \beta) \end{bmatrix} \begin{bmatrix} \tilde{J}_z(\alpha) \\ \tilde{J}_y(\alpha) \end{bmatrix} = \begin{bmatrix} \tilde{E}_z(\alpha, h_1) \\ \tilde{E}_y(\alpha, h_1) \end{bmatrix} \tag{4}$$

where $\tilde{Z}_{zz}(\alpha, \beta)$, $\tilde{Z}_{zy}(\alpha, \beta)$, $\tilde{Z}_{yz}(\alpha, \beta)$, and $\tilde{Z}_{yy}(\alpha, \beta)$ represent the impedance of Green's function elements. In the above equation, $\tilde{J}_z(\alpha)$ and $\tilde{J}_y(\alpha)$ are the Fourier transforms of the current densities on the metal strip which can be expanded in terms of known basis functions as

$$\tilde{J}_{z,y}(\alpha) = \sum_{m=1}^{M,N} (C_m, D_m)\tilde{J}_{zm,ym}(\alpha) \tag{5a, b}$$

whose explicit expressions are given by

$$\begin{Bmatrix} \tilde{J}_{zm}(\alpha) \\ \tilde{J}_{ym}(\alpha) \end{Bmatrix} = \frac{W\pi}{4r} \begin{Bmatrix} \sin(\alpha(d + W/2))[J_0(\alpha W/2 + (m-1)\pi) + J_0(\alpha W/2 - (m-1)\pi)] \\ \cos(\alpha(d + W/2))[J_0(\alpha W/2 + m\pi) - J_0(\alpha W/2 - m\pi)] \end{Bmatrix} \tag{6a, b}$$

where J_0 is the Bessel function of order zero. Note that both $\tilde{J}_{zm}(\alpha)$ and $\tilde{J}_{ym}(\alpha)$ in eqns. 6a, b have been adjusted so that the metal strip may be arbitrarily displaced anywhere from the centre of the housing along the air-anisotropic-substrate interface.

Finally, the standard Galerkin method is applied to find the propagation contant β [7]. This is done by substituting eqns. 5a, b into eqn. 4 and forming appropriate inner products among $\tilde{J}_{zm}(\alpha)$s, and independently among $\tilde{J}_{ym}(\alpha)$s. The characteristic or secular equation of the resulting matrix system is then obtained and solved for the propagation contant β by searching for its roots [7].

3 Results and concluding remarks

In this Section, we examine the behaviour of the effective dielectric constant $\varepsilon_{eff} = (\beta/k_0)^2$ when the shielded microstrip is printed on the anisotropic substrate and is displaced from the centre of the waveguide housing. The two substrate materials under consideration are the boron nitride and the PTFE cloth. The cloth material is biaxial, whereas boron nitride is uniaxial. The two specific properties that are examined include the frequency response of ε_{eff} under the perfect alignment of the two co-ordinate systems, and the response of ε_{eff} under the misalignment of the axes at any angle θ, both as functions of S.

The validation of the formulation and its numerical implementation was carried out in two forms. First, the offset parameter S was set equal to zero and the dispersion properties of the microstrip were compared to those presented earlier in Reference 2. The agreement between them was found to be very good, and as these results are available [2], they were omitted here. Next, the effective dielectric constant was also computed for the asymmetric microstrip whose substrate is isotropic $\varepsilon_r = 2.2$, and whose physical dimensions are $b = 3.556$ mm, $h_1 = 0.254$ mm, $h_2 = 3.429$ mm, and $W = 0.3$ mm. The numerical results at 33 GHz for this structure are shown in Fig. 1, and as can be seen, the agreement between the calculated and existing data [8] is very good.

When the substrate is 0.508 mm thick and it is mounted inside a waveguide housing with dimensions $b = 3.556$ mm and $(h_1 + h_2) = 3.556$ mm, Fig. 2 shows how the effective dielectric constant for the boron nitride and PTFE cloth varies with frequency for different values of S. For this set of physical dimensions of the structure, all data are computed from 5 GHz to 40 GHz with $\theta = 0°$. In general, the effective dielectric constant increases with the frequency for all values of S. However, as the strip moves away from the centre of the housing ($S = 0$), ε_{eff} decreases slowly for small displacement values, and then drops off considerably when the strip is situated close to the side wall of the waveguide. As the strip offset parameter S increases from 0.0 mm to 1.4 mm,

from 4.58% to 7.03% and 3.73% to 7.04% (i.e. from when $S = 0$ mm to when $S = 1.4$ mm) at 10 GHz and 40 GHz, for the PTFE cloth and boron nitride, respectively.

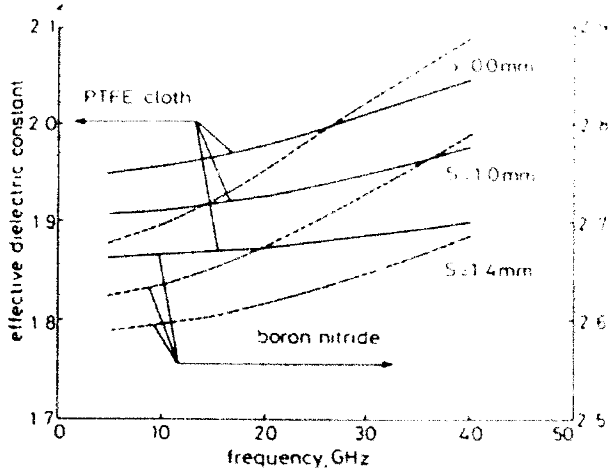

Fig 2 *Frequency response of effective dielectric constant against S of microstrip line on boron nitride and PTFE cloth*

Boron nitride: $\varepsilon_1 = 3.4$; $\varepsilon_2 = 5.12$; $\varepsilon_3 = 5.12$
PTFE cloth: $\varepsilon_1 = 2.45$; $\varepsilon_2 = 2.89$; $\varepsilon_3 = 2.95$
$b = 3.556$ mm $h_1 = 0.508$ mm $h_2 = 3.048$ mm $W = 0.508$ mm $\theta = 0°$

The response of the effective dielectric constant of the line when the waveguide and the material co-ordinate systems are misaligned is examined next. All physical dimensions are still the same as those specified earlier, and the same two substrates are used. The frequency this time is fixed at 20 GHz, and for each substrate, a family of curves, just like those presented before, are generated with respect to different values of the offset parameter S. It can be observed from Fig. 3 that as the rotation angle increases from 0° to 90°, the effective dielectric constant is becoming larger also. Again, a similar trend to that observed earlier is evident as S increases from 0.0 mm to 1.4 mm. Specifically, the value of the effective constant ε_{eff} can be reduced by displacing the strip farther from the centre of the housing. When the misalignment angle θ is 90°, the corresponding changes in ε_{eff} for all values of S appear to be more profound than those at $\theta = 0°$ for both types of substrates. These variations are expected to become even larger as the operating frequency moves anisotropy must be account for properly in the design of millimeter-wave integrated circuits.

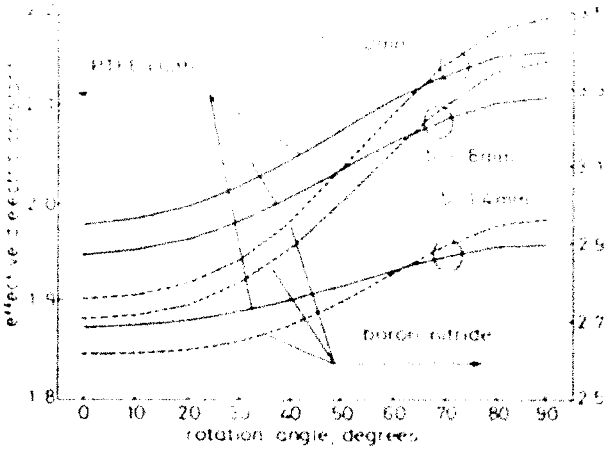

Fig. 3 *Rotation response of effective dielectric constant against S of microstrip line on boron nitride and PTFE cloth*

Boron nitride: $\varepsilon_1 = 3.4$; $\varepsilon_2 = 5.12$; $\varepsilon_3 = 5.12$
PTFE cloth: $\varepsilon_1 = 2.45$; $\varepsilon_2 = 2.89$; $\varepsilon_3 = 2.95$
$b = 3.556$ mm; $h_1 = 0.508$ mm; $h_2 = 3.048$ mm; $W = 0.508$ mm; $f = 20$ GHz

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